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A Gamma type Stirling refrigerator optimization: An experimental and analytical investigation

Alireza Batooei, Ali Keshavarz*

Mechanical engineering faculty, K. N. Toosi University of Technology, Vanak Sq. Mollasadra St., Tehran, Iran

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ABSTRACT

In this study, multi-objective optimization of a Gamma type Stirling refrigerator is carried out based on the experimental and analytical results. The cooling capacity and the coefficient of performance (COP) are experimentally investigated for helium and air. Beside to helium and air, carbon dioxide is also considered as the working fluid in the simulation. A non-ideal adiabatic analysis is developed for the simulation. The experimental and simulation results showed that the cooling capacity increases continuously with the rotational speed where the COP has a maximum value. The optimum COP value for helium occurs at higher rotational speed than that of the air.

The Design of Experiment (DOE) method is used for multi-objective optimization. Three parameters namely COP, cooling capacity and pressure drop are investigated in this optimization study. Only helium and carbon dioxide are considered for optimization because of their higher specific heat capacity and enthalpy with respect to air. The optimum working pressure for the carbon dioxide takes place at lower pressure than that of helium. When the importance and weight factors equal one, the optimum point for helium is obtained at working pressure and rotational speed of 9 bar and 451.1 rpm, respectively. Where, the optimum point for carbon dioxide is found at working pressure and rotational speed of 3.3 bar and 798.5 rpm, respectively.

Optimisation d'un réfrigérateur Stirling de type Gamma: étude expérimentale et analytique

Mots-clés: Réfrigérateur Stirling; Expérimental; Analytique; Optimisation à objectifs multiples; Méthode DOE

1. Introduction

The air pollution and global warming are the two main concerns of international community in these years. It seems Stirling engines have a good potential for using in the future because of some advantages like external combustion, fuel flexibility and capability to work in the reverse cycle for refrigeration operating. The traditional working fluids in the Stirling refrigerator are helium, air and carbon dioxide. Despite of many conventional refrigerants these fluids are not harmful to the environment. Therefore, any effort for substitution of the ordinary refrigerant in refrigeration systems is welcome by the environmental and industrial researchers.

Stirling refrigerator and cryocooler have been investigated by many researchers (Tyagi et al., 2004; Chen et al., 2014; Araoz et al., 2015; Finkelstein and Polonski, 1959). It seems Finkelstein and Polonski (1959) are pioneer to studied domestic refrigerator utilizing Stirling cycle. Atrey et al. (1990) developed cyclic simulation of Stirling refrigerator. They calculated pressure losses of each component in the cycle such as heater and cooler. They assumed adiabatic compression and isothermal expansion processes in their analysis.

Tyagi et al. (2002) investigated the impact of some parameters such as the source temperature and specific heat constant on the maximum cooling capacity by using control volumes technique. They showed that COP of a *V*-type Stirling refrigerator is

* Corresponding author.
E-mail addresses: abatooei@mail.kntu.ac.ir (A. Batooei), keshvarz@kntu.ac.ir (A. Keshavarz).

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Nomenclature

A_{k1}	connecting pipe internal wetted area (m^2)
A_{k2}	cooler internal wetted area (m^2)
A_s	wetted area (m^2)
C_P	specific heat at constant pressure (J/Kg K)
C_V	specific heat at constant volume (J/Kg K)
C_f	friction coefficient
C_{st}	steel specific heat (J/Kg K)
COP	coefficient of performance
CVC	compression Clearance volume of Compression (m^3)
CVE	clearance volume of Expansion (m^3)
D	tube diameter (m)
d_i	individual desirability for the *i*th response
e	internal energy (J/kg)
$T_{h,\,out}$	water outlet temperature of heater (K)
H	enthalpy(J/kg)
h	convective heat transfer coefficient (W/m^2K)
I	current (A)
L_i	lowest acceptable value for *i*th response
M	total mass of gas (kg)
$\dot{m}_c$	water flow rate of cooler (kg/s)
$\dot{m}_h$	water flow rate of heater (kg/s)
m_i	*i*th control volume mass
N	engine speed (rpm)
Nu	Nusselt number
Nu_{s-ave}	space-cycle averaged Nusselt number
P	pressure (Pa)
$\dot{Q}$	heat transfer (W)
$\dot{Q}_h$	heat transferred to heater (W)
$\dot{Q}_k$	heat transferred to cooler (W)
$\dot{Q}_r$	heat transferred to regenerator (W)
$\dot{Q}_{r,loss}$	regenerator heat loss (W)
R	gas constant (J/kg K)
Re_w	kinetic Reynolds number, $\rho WD^2/\mu$
r_i	weight of desirability function of *i*th response
r_1	COP weight factor
r_2	cooling capacity weight factor
r_3	pressure drop weight factor
T	time (s)
T	temperature (K)
$T_{c,\,in}$	water inlet temperature of cooler (K)
$T_{c,\,out}$	water outlet temperature of cooler (K)
$T_{h,\,in}$	water inlet temperature of heater (K)
$\dot{Q}_l$	cooling capacity (W)
T_i	target value for *i*th response
V	volume (m^3)
$\hat{V}$	voltage (V)
W	angular velocity (rad/s)
w_i	importance of the *i*th response
w_1	COP importance factor
w_2	cooling capacity importance factor
w_3	pressure drop importance factor
W_{loss}	loss work (J)
$\dot{W}_c$	cooler power lost (W)
$\dot{W}_h$	heater power lost (W)
$\dot{W}_e$	electrical Power (W)
$\dot{W}_{in}$	input power (W)
$\dot{W}_r$	regenerator Power lost (W)
y_i	predicted value of *i*th response

Greek letters

η_m	mechanical efficiency
η_e	electrical efficiency
θ	Crank angle (rad)
μ	dynamic viscosity (Pa.s)
ρ	density (kg/m^3)
ϕ	phase angle (degree)
ΔP	pressure drop (Pa)
ΔP_m	pressure drop of specific pipe
ΔP_m	pressure drop of specific component
λ_e	Crank radius to expansion connecting rod ratio
λ_c	Crank radius to compression connecting rod ratio

Subscripts and superscripts

B	body
C	compression
c,in	cooler inlet
c,out	cooler outlet
E	expansion
f	fluid
H	heating
in	inlet
out	outlet
reg	regenerator
SE	expansion swept volumes
SC	compression swept volumes
w	wall

comparable with an ordinary vapor pressure refrigeration system. The Performance of a prototype domestic Stirling refrigerator was considered by Le'an et al. (2009). The input work and COP were studied at various rotational speeds and working pressures. Thermodynamic simulation was developed for a non- ideal adiabatic model. The new pressure drop estimation was added to this research. Nitrogen and helium were used for comparison in the experimental and simulation results.

Wu et al. (2007) proposed a new configuration type of Stirling refrigerator for domestic usage. A thermal buffer tube is used between expansion piston and cold-end side of the refrigerator. The Stirling refrigerator working pressure and frequency in their experimental study were set to 25 bar and 15 Hz, respectively. The working fluid was helium and the minimum temperature, COP and cooling capacity were −78 °C, 0.64 and 200 W, respectively. The cooling temperature in terms of time was reported by Scollo et al. (2008). They tested a refrigerator with hydrogen where the pressure and rotational speed were 7 bar and 200 rpm, respectively. They reported that the cooling temperature became stable after about 25 min.

Li et al. (2016) analyzed the effect of losses include regenerator imperfection, seal leakage clearance, displacer shuttle and viscous friction phenomena on the performance of a Gamma type Stirling engine by utilizing energy and exergy method. They used the isothermal method and finite speed thermodynamic for their solution. They found out that the regenerator imperfection and clearance leakage are the two main loss factors, which could be quantified.

Ataer and Karabulut (2005) used thermodynamic analysis to simulate a *V*- type Stirling refrigerator. They divided the Stirling refrigerator into 14 fixed control volumes. The heat transfer coefficients and the cooler and heater wall temperatures were assumed to be constant. They demonstrated that the enhancement of heat transfer area and heat transfer coefficients result in higher COP. The performance of a *V*-type Stirling refrigerator was analyzed by Tekin and Ataer (2010). They used hydrogen, helium and air as the working fluid. The temperature during the compression and expansion process was assumed to be constant where the regenerator was assumed to be adiabatic.